Energy and Indoor Air Quality Benchmarking of the NIST Net-Zero Energy Residential Test Facility (NZERTF)

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ABSTRACT

The National Institute of Standards and Technology (NIST) designed and built a residence that could generate, through the use of renewable energy systems, the amount of energy required by a virtual family of four over one year. The Net-Zero Energy Residential Test Facility (NZERTF) utilizes enhanced air sealing techniques, high levels of thermal insulation, and high-efficiency equipment to meet the comfort levels and functions of the virtual occupants while lowering energy consumption. Adequate ventilation and reduced indoor contaminant sources were also key design features to support occupant health and comfort.

The purpose of this paper is to assess how current and new approaches to benchmarking apply to high-performance homes. This study compares the annual energy use intensity (EUI) of the NZERTF (33.8 kWh/m^2 or 10.7 kBtu/ft^2) to the EUIs of existing single-family detached homes in the Mixed-Humid climate zone and the entire United States. The study presents the NZERTF's Home Energy Rating System (HERS) index (-6 with on-site power generation, 31 without), Home Energy Yardstick score (10), and the HUD Energy Benchmark Tool score (97). In contrast, indoor air quality (IAQ) benchmarking is challenging and not yet standardized. Concentrations of formaldehyde in the unoccupied NZERTF are typically above long-term non-carcinogenic relative exposure limits, but in the lowest 10th percentile compared to recent surveys of new, occupied homes. Concentrations of other volatile organic compounds (VOCs) in the NZERTF tend to be higher than these other homes, but below concentrations resulting in health concerns (except for acetaldehyde).

A truly high-performance residence must exceed both energy and IAQ benchmarks, as well as those related to thermal comfort, water consumption, and others. This work highlights the challenge in finding appropriate benchmarks to which a high-performance home should be compared.

Introduction

The Department of Energy (DOE) defines benchmarking as "the practice of comparing the measured performance of a device, process, facility, or organization to itself, its peers, or established norms, with the goal of informing and motivating performance improvement" (DOE 2016). One of the challenges in building energy benchmarking is identifying a representative building or set of buildings for comparison. An ideal benchmarking process entails comparing the rated building performance to that of reference buildings within the same climate zone, of the same size, housing type, number of occupants and occupant activities. For energy benchmarking of residential buildings, an extensive set of reference data can be obtained from the DOE Residential Energy Consumption Survey (RECS) (EIA 2009). The most recent version of RECS surveyed over 12,000 residential buildings of all types, and data were extrapolated to estimate energy use and building characteristics of the 114 million residences in the nation's housing stock. The U.S. Department of Housing and Urban Development (HUD) carried out a similar, but less extensive survey, with public housing authorities to form the basis of their benchmarking tool (2007). Some energy benchmarking tools like the Residential Energy Services Network (RESNET) Home Energy Rating System (HERS) rely on simulations to generate a representative reference, which is the same building to the one that is rated, but modeled to minimum energy code requirements (ANSI/RESNET 2014).

Indoor environmental benchmarking efforts are less mature than those for energy, but are also very important. Minimizing occupant exposures to airborne contaminants should define IAQ benchmarking, regardless of whether it is achieved via increased ventilation (at an energy cost), filters (energy and financial cost), and/or reduced source emissions (potential financial cost). There are many challenges associated with benchmarking IAQ, however. These include identifying the most important pollutants to consider and selecting the concentration reference values to use for comparison. For example, benchmark comparisons can be made to health impact data or to concentrations in other existing homes. Further, if health impacts are used for comparisons, one must distinguish between benchmarks that refer to immediate or acute impacts and those that refer to long-term or chronic impacts. For many chemicals, there are no known health impact standards or recommendations, and comparisons can only be made to measured concentrations in existing housing stock.

In this work, energy and IAQ benchmarking was conducted at the Net-Zero Energy Residential Test Facility (NZERTF) located in Gaithersburg, MD, USA. This home was built as a research facility to assess various technologies and operational strategies for achieving net-zero energy operation through effective construction techniques, efficient equipment, and the use of photovoltaics. The house has a living area of 252 m^2 (2712 ft^2) and basement floor area of about 135 m^2 (1453 ft^2). Electrical energy and water use of two adults and two children is simulated throughout the year to provide a repeatable experiment to assess performance (Omar and Bushby 2013). The home was built with a highly insulated building envelope, an air and moisture control membrane. To comply with the minimum ventilation requirements in the ASHRAE Standard 62.2-2010 (ASHRAE 2010), a Heat Recovery Ventilator (HRV) was sized to deliver 137 $m^3\ h^{-1}$ of outdoor air but actually delivered 171 $m^3\ h^{-1}$ using the available fan speeds in the unit. Further details on the design of the home are provided by Pettit et al. (2014). This paper describes several approaches used to assess how this home's energy and indoor environmental quality performance compares to typical homes.

Energy Benchmarking of the NZERTF

NZERTF vs. Average Energy Use / Energy Use Intensity

One method to compare the NZERTF to reference housing stock is to use the Energy Use Intensity (EUI) metric or annual energy used per unit floor area. Similar metrics such as annual energy used per home, annual energy used per bed, or annual energy used per household member (Pérez-Lombard et al. 2009) exist but are less often used.

The NZERTF data acquisition system measured electrical energy every minute, both what was used by the virtual occupants of the home and the energy generated by the photovoltaic system. Details on the monitoring methodology can be found in Davis et al. (2014). The NZERTF consists of 252 m^2 (2712 ft^2) of living area (first and second floors) and 135 m^2 (1453 ft^2) of basement space, amounting to a total conditioned floor area of 387 m^2 (4165 ft^2). To remain consistent with the RECS survey, which monitors characteristics and energy consumption of a nationally representative sampling of homes, we did not include the detached garage or the attic in this analysis. The RECS survey only includes the garage if it is attached and conditioned and the attic if it is conditioned or finished, as well as the basement and other living areas of the home. During the first year of the home's operation, the NZERTF consumed a total of 13,039 kWh (44.5 MMBtu) of energy; thus, the EUI of the home is 33.8 kWh/m^2 (10.7 kBtu/ft^2).

The first five rows of Table 1 present average energy use per home and average EUIs, by housing characteristic, from the 2009 RECS database. The next three rows of Table 1 show data from the combined housing stock sharing two or more housing characteristics with the NZERTF. The NZERTF consumes approximately 49.6 % of the total energy of the average home in the U.S. (26,300 kWh/yr or 89.6 MMBtu/year) and has 23.5 % of its energy use intensity (144 kWh/m^2 or 45.5 kBtu/ft^2). The NZERTF performs similarly when compared to single-family detached homes and to all home types within the Mixed-Humid climate zone (the location of the NZERTF), with the NZERTF having 25.1 % and 23.5 % of their average EUIs, respectively.

Table 1. RECS 2009 Energy Performance Indicator (EPI) for Various Categories

Housing Characteristic	Avg. Energy Used per Yr		Avg. EUI	
	[kWh]	[*MMBtu*]	[kWh/m^2]	[*kBtu/ft^2*]
Average U.S. home	26,259	*89.6*	143.5	*45.5*
Single-Family Detached	30,978	*105.7*	134.4	*42.6*
Mixed-Humid (M-H) Climate Zone	26,816	*91.5*	140.1	*44.4*
Home built between 2000 and 2009	26,816	*91.5*	117.0	*37.1*
Total floor area ≥ 370 m^2 (4000 ft^2)	46,159	*157.5*	93.1	*29.5*
Single-Family Detached in M-H zone	31,359	*107.0*	129.0	*40.9*
Home built between 2000 and 2009, floor area ≥ 370 m^2 (4000 ft^2)	48,005	*163.8*	91.5	*29.0*
Single-Family Detached in M-H zone, built between 2000 to 2009, and floor area ≥ 370 m^2 (4000 ft^2)	45,719	*156.0*	89.9	*28.5*
NZERTF	**13,039**	***44.5***	**33.8**	***10.7***

One factor contributing to the low energy use intensity of the NZERTF is its size. In fact, home age and size are linked. Both the U.S. Census (Sarkar 2011) and the U.S. Energy Information Administration (EIA) (2015) have established the steady rise of detached single-family home floor area from 1980 to 2009; the average U.S. home grew 18.9 % in size in that period. The NZERTF is closer in energy performance to homes built in the last decade (EUI = 117.0 kWh/m^2 or 37.1 kBtu/ft^2) and even closer to other homes that have a total floor area of 370 m^2 (4000 ft^2) or more (EUI = 93.1 kWh/m^2 or 29.5 kBtu/ft^2). Furthermore, the combined factors of a home being built between 2000 and 2009 and having floor area greater than 370 m^2 (4000 ft^2) have a larger relation to the NZERTF EUI than homes that are detached single-family homes and are in the Mixed-Humid climate zone. The EUI of the former set of homes is 89.9 kWh/m^2 (28.5 kBtu/ft^2), and the EUI of the latter set is 129.0 kWh/m^2 (40.9 kBtu/ft^2). Comparing the NZERTF to houses of similar construction requires examining a subset of the RECS database that includes new, single-family detached housing located in Mixed-Humid climate zone with floor areas of 370 m^2 (4000 ft^2) or more. This group consumed on average of 89.9 kWh/m^2 (28.5 $kBtu/ft^2$) in 2009, compared to 33.8 kWh/m^2 (10.7 $kBtu/ft^2$) for the NZERTF (37.5 %).

HERS Index

In 1995, the National Association of State Energy Officials and Energy Rated Homes of America founded RESNET to develop a national standard for home energy performance ratings (RESNET 2016b). The RESNET process entails a visit from a certified home energy rating professional, during which the rater inspects characteristics such as insulation levels, window type, wall-to-window ratio, heating/cooling system efficiency, water heating system efficiency, solar orientation, and any renewable technologies (RESNET 2016b). The rater also collects airtightness data from blower door and duct leakage tests. HERS software calculates a score comparing a home's simulated energy use to that of the RESNET reference home. The reference home is simulated mostly to meet the 2006 International Energy Conservation Code and has shared characteristics to the rated home, such as gross floor area, foundation type, and fuel type (ANSI/RESNET 2014). A HERS Index Score of 100 means the rated home's predicted energy use is equivalent to that of the reference home. The lower the score, the more energy efficient the home. A HERS index of 80, for example, means that the rated home uses 20 % less energy compared to the reference home. Zero and negative scores of HERS are possible, since the calculation factors in on-site power production that offsets the electrical energy consumed in the home.

Including the solar thermal and photovoltaic systems on the home, the NZERTF has a HERS rating of -6; thus, the NZERTF *produces* 6 % more of the equivalent electrical energy that the RESNET reference home *consumes* overall. A recent report by RESNET (2016a) highlighted that the national average HERS index for net-zero homes was -7 (see Table 2).

Table 2. HERS index scores of non-net-zero energy and net-zero energy homes

Home type	HERS Index
Average U.S. net-zero home (n=185)	-7
Average Maryland net-zero home (n=2)	-2
NZERTF (as built)	**-6**
Average U.S. home (n=190,180)	62
Average Maryland home (n=5,903)	57
NZERTF (without on-site power production from PV)	**31**

Similar to the way energy benchmarking the NZERTF using RECS EUI data solely considered energy consumed, the HERS index can also be used to benchmark the NZERTF without the PV system. The HERS index in this case is 31; that is, the NZERTF without power generation on site is 69 % more energy efficient than the reference home. RESNET reports that the average HERS-rated home in the United States in 2015 received a score of 62 (2016c). Maryland homes rated by RESNET scored slightly better (average of 57) than the average rated U.S. home, possibly due to the fact that the state adopted the 2012 IECC and 2015 IECC building codes when they became available.

Benchmarking Tools for the Homeowner

While annual energy use/EUI and HERS index benchmarking provide useful comparisons of a rated home to the national building stock and a well-defined reference home, respectively, these benchmarking methods require expertise most homeowners do not have. They require careful tabulation of floor area from floor plans, detailed information about the walls, windows, appliances, and heating and cooling systems in the home, as well as results from air leakage tests. There are several simpler benchmarking tools available to the homeowner that can be used by inputting only a few housing characteristics, utility data, and location information.

The Home Energy Yardstick. The U.S. Environmental Protection Agency (EPA) Energy Star program has developed the Home Energy Yardstick rating system to provide homeowners with a performance-based energy comparison to similar homes (2016a). The tool uses 12 months of utility data with a statistical algorithm to control for the effects of location, home size, and number of occupants (all are inputs). The Yardstick algorithm compares the home to data obtained from the RECS. The Yardstick outputs a score from 1 to 10, where a "1" rated home uses more energy over 12 months than all comparable homes and a "10" performs at the top of the group. Using electrical energy consumption between July 2013 and June 2014, the NZERTF received a Yardstick score of 10.

HUD Utility Benchmarking Tool. The U.S. Department of Housing and Urban Development (HUD) has a spreadsheet tool to compare energy and energy costs of all types of residential buildings (single- and multi-family homes, attached and detached homes, etc.) to similar homes under public housing authorities (PHAs) (2007). Like the Home Energy Yardstick, the individual seeking a rating inputs zip code, annual energy used from all fuel types, and conditioned space floor area. A regression model algorithm generates the benchmarking score based on data voluntarily submitted for over 9,100 buildings by almost 350 PHAs nationwide. The tool outputs a score from 1 to 100, where a "50" is the HUD median home; the higher the score, the better. The HUD utility benchmarking tool gives the NZERTF a score of 97 compared to similar homes, with the HUD equivalent home (score = 50) having an EUI of 76.7 kWh/m^2 (24.3 kBtu/ft^2).

Indoor Air Quality Benchmarking of the NZERTF

The NZERTF was sampled monthly over 15 months to determine chemical concentrations of over 30 different chemicals (Poppendieck et al. 2015).[1] The chemicals measured in this study are not a comprehensive list of contaminants of concern. For example, fine particulate matter was not analyzed. Two sets of benchmarks were chosen to compare the NZERTF IAQ data: 1) U.S. governmental (federal and state) health guidelines, and 2) concentrations measurements from newly constructed homes.

Health Benchmarks

There are a wide range of health impacts that could be chosen as a health benchmark. Since the NZERTF is simulating a typical residence that would be occupied at least 15 hours a day, the most appropriate and conservative health benchmark would be a chronic rather than

[1] Note that indoor concentrations are shown in this document, while indoor minus outdoor concentrations are listed in Poppendieck et al. (2015).

acute benchmark. Seven of the 36 chemicals analyzed in the NZERTF have either a California Office of Environmental Health Hazard Assessment (OEHHA) chronic relative exposure level (CREL), an EPA inhalation reference concentration (RfC), or an EPA action level as shown in Table 3. Both CREL and RfC values define a concentration that is deemed to have no deleterious or cancerous impacts after a lifetime of exposure, e.g. eye, nose, or throat irritation.

Five of the analyzed chemicals have been classified as a known, probable, or possible human carcinogen according to the International Agency for Research on Cancer (IARC, references in Table 3). The EPA typically does not identify an acceptable exposure level to a carcinogen; rather, it defines unit risk factors to estimate cancer risk from chronic exposure to the chemical. Three of the studied chemicals have EPA inhalation unit risk factors (formaldehyde, acetaldehyde, and benzene). A user can choose an acceptable risk level and use the unit risk factor to determine the chemical concentration that correlates to that risk. A risk level of 1 cancer in 1,000,000 people is a typical risk level chosen for general public environmental exposure (e.g. Superfund sites), and a risk level of 1 cancer in 10,000 is a typical level chosen for individual workplace exposures. For the purpose of comparisons to the NZERTF concentration data these two risk levels were evaluated: 1 in 10,000 (10^{-4}) and 1 in 1,000,000 (10^{-6}).

The three chemicals with EPA unit risk factors (formaldehyde, acetaldehyde, and benzene) are highlighted below. For three of the other four chemicals listed in Table 3, the NZERTF concentrations were at least an order of magnitude below the CREL values.

Acetaldehyde. Acetaldehyde can be found in the indoor environment as the result of emissions from polyurethane foams and from secondary reactions of ozone and alkenes such as ethane. Acetaldehyde is considered a probable human carcinogen by IARC (2009). In monthly testing between May 2013 and July 2014, the NZERTF geometric mean concentration was 17.0 $\mu g/m^3$, with a maximum of 35.3 $\mu g/m^3$. A total of 13 of the 15 NZERTF samples exceeded the EPA RfC benchmark (9 $\mu g/m^3$), and all of the samples exceeded the carcinogenic inhalation exposure level correlating to a risk level of 10^{-6} (0.5 $\mu g/m^3$), indicating the NZERTF was frequently above these health benchmarks during normal operation. However, none of the samples exceeded the OEHHA CREL (140 $\mu g/m^3$) or the carcinogenic inhalation exposure level correlating to a risk level of 10^{-4} (50 $\mu g/m^3$). For reference, the outside acetaldehyde geometric mean concentration during the sampling events was 1.0 $\mu g/m^3$.

Benzene. Benzene can be released into the indoor environment from adhesives, sealants and attached garages with gasoline based engines. Benzene is classified as a human carcinogen (IARC 2012). The concentration of benzene in the NZERTF was typically below the method detection limit (MDL), always less than 1.1 $\mu g/m^3$, and never greater than 0.1 $\mu g/m^3$ above the outside concentration. For all samples, the benzene concentration was below the CREL value. The samples that exceeded the carcinogenic benchmark concentration correlating to a 10^{-6} risk level (0.45 $\mu g/m^3$) were typically attributable to elevated outdoor benzene levels.

Table 3. Summary of monthly chemical concentration measurements in NZERTF. (Numbers after the ± symbols are geometric standard deviations. Last column is number of measurements that exceeded a health reference level.)

Chemical	IARC Designation (Reference)	Agency (Ref)	Type	Bench-mark Conc.[a]	Geometric Mean of NZERTF Conc.	Times Benchmark Exceeded
Acetaldehyde	Probable Human Carcinogen (IARC 2009)	EPA (1988)	Carcinogenic 10^{-6}	0.5 μg/m^3	17 ± 1.7 μg/m^3	15
		EPA (1988)	Carcinogenic 10^{-4}	50 μg/m^3		0
		EPA (2000a)	RfC	9 μg/m^3		13
		OEHHA (2016)	CREL	140 μg/m^3		0
Benzene	Human Carcinogen (IARC 2012)	EPA (2000b)	Carcinogenic 10^{-6}	0.45 μg/m^3	MDL[b]	0
		EPA (2000b)	Carcinogenic 10^{-4}	45 μg/m^3		0
		OEHHA (2016)	CREL	3 μg/m^3		0
Formaldehyde	Human Carcinogen (IARC 2006)	EPA (1989)	Carcinogenic 10^{-6}	0.08 μg/m^3	9.2 ± 1.7 μg/m^3	15
		EPA (1989)	Carcinogenic 10^{-4}	8 μg/m^3		6
		OEHHA (2016)	CREL	9 μg/m^3		9
Ethylene Glycol	Not Listed	OEHHA (2016)	CREL	400 μg/m^3	14.2 ± 2.3 μg/m^3	0
Radon	Human Carcinogen (IARC 1988)	EPA (2016b)	Action Level	4 pCi/L	1.1 pCi/L	1[c]
Styrene	Possible Human Carcinogen (IARC 2002)	OEHHA (2016)	CREL	900 μg/m^3	2.6 ± 2.2 μg/m^3	0
Toluene	Not Listed	OEHHA (2016)	CREL	300 μg/m^3	2.2 ± 3.9 μg/m^3	0

[a] Benchmarks for carcinogens (known, probable, and possible) are the result of using the unit risk factors to calculate concentration that corresponds to a risk.
[b] MDL=method detection limit
[c] A total of twelve Radon samples were taken in the year (basement, first floor and second floor each quarter).

Formaldehyde. Formaldehyde can be released into the indoor environment from building materials including resins, insulation, and composite wood products (particleboard, medium density fiberboard, laminate flooring). Formaldehyde is classified as a human carcinogen (IARC 2006). The NZERTF had a geometric mean of 9.2 $\mu g/m^3$ with a maximum of 13.8 $\mu g/m^3$. A total of 9 of the 15 samples exceeded the non-cancer OEHHA CREL (9 $\mu g/m^3$). The NZERTF was below the CREL formaldehyde concentration only during winter months. All samples exceeded the carcinogenic benchmark concentration correlating to a 10^{-6} risk level (0.08 $\mu g/m^3$), while six samples exceeded the carcinogenic benchmark concentration correlating to a 10^{-4} risk level (8 $\mu g/m^3$). For reference, the outside formaldehyde geometric mean concentration during the sampling events was 1.4 $\mu g/m^3$.

Comparison Benchmarks

Many chemicals found indoors have no relevant health-based standard for comparison. Maddalena et al. (2012) found that of 235 chemicals identified in 108 new California homes, only 31 % had relevant health-based guidelines and less than 10 % had CRELs. An alternative benchmarking approach is to compare chemical concentrations to measurements in other residential structures. Two known recent, relatively large data sources for U.S. homes published by Hult et al. (2015) and Offermann (2009) are employed in this comparison.

Hult et al. (2015) analyzed 13 homes for formaldehyde and acetaldehyde concentrations. The homes were built with low-emitting materials meeting Leadership in Energy and Environmental Design (LEED)-certified/Indoor airPLUS criteria (further referred to as the "Indoor airPLUS study"). The furnished, occupied homes were less than five years old prior to the sampling event. Offermann (2009) measured 22 VOC concentrations in 108 new, single-family, occupied, detached homes built using standard construction methods in California (further referred to as the "California New Homes Study" (CNHS)). These homes were not built with specifications for low-emitting building materials. The homes were constructed between 2002 and 2004 and occupied at least one year prior to sampling. The California study determined the geometric mean concentration, a cumulative frequency distribution for each of the measured concentrations, and concentration percentiles for each chemical.

There are some differences between the homes in the two studies and the NZERTF that need to be taken into consideration when comparing their chemical concentrations. The homes in both studies were fully furnished and occupied, while the NZERTF was not furnished other than with built-in cabinets and had no occupants. The air change rate for homes in the Indoor airPLUS study (mean 0.26 h^{-1}, measured while VOC concentrations were measured, standard deviation 0.24 h^{-1}) and the CNHS (median 0.26 h^{-1}, measured during VOC sampling, mean 0.48 h^{-1}, standard deviation 0.78 h^{-1}) were higher than that of the NZERTF (mean 0.15 h^{-1}, total of measured mechanical ventilation and modeled infiltration during normal operation). It should be noted that 0.15 h^{-1} was calculated using the volume of the basement, 1st and 2nd floors, and attic. Given that the basement and attic were not directly ventilated by the HRV, 0.15 h^{-1} is not a measure of the removal rate of contaminants from the 1st and 2nd floors, where the air samples were taken. Nonetheless, the basement and attic were included in the calculated air change rate of 0.15 h^{-1} since both passively receive air from the 1st and 2nd floors through transfer grilles. Both the basement and attic are also within the conditioned space. If the basement and attic were not included, then the air change rate would be approximately 0.22 h^{-1}, not accounting for infiltration. The CNHS and studies both utilized perfluorocarbon tracer tests, which represented the total outdoor air ventilation rate delivered to the indoors. Given the lower air change rate in the NZERTF compared to the average homes in both studies, one would expect the concentration in the NZERTF to be higher for equal emission rates.

Table 4 compares the ten chemicals that were measured in both the CNHS Offermann (2009) and the NZERTF (Poppendieck et al. 2015). Formaldehyde and acetaldehyde comparisons to both the Indoor airPLUS study and the CNHS are highlighted below. The results of the remaining eight chemicals are discussed more briefly.

Table 4. A comparison of geometric means of ten chemical concentrations (μg/m^3) analyzed in both the NZERTF and the CNHS. The percentile is the minimum percentile rank (10 %, 25 %, 50 %, 75 %, or 90 %) statistically-derived from the CNHS, that the NZERTF did not exceed.

Compound	Max NZERTF Conc.	NZERTF Geometric Mean Conc.	Indoor airPLUS Homes Geometric Mean (Hult et al. 2015)	CNHS Geometric Mean Conc. (Offermann 2009)	NZERTF Percentile in the CNHS Study (Lower is better)[a]
Acetaldehyde	35.3	17.0 ± 1.7	33 ± 1.5	19 ± 2.3	50 %
Formaldehyde	13.8	9.2 ± 1.4	42 ± 1.4	36 ± 1.9	10 %
Hexanal	190	44.7 ± 2.5	N/A	7.0 ± 2.7	>90 %
Toluene	255	2.2 ± 3.9	N/A	9.5 ± 2.5	10 %
Styrene	9.8	2.6 ± 2.2	N/A	0.9 ± 2.8	90 %
1,2,4-Trimethylbenzene	7.8	3.7 ± 1.6	N/A	1.0 ± 3.2	90 %
Phenol	3.8	1.8 ± 1.6	N/A	1.6 ± 2.0	75 %
Ethylene glycol	37.6	14.2 ± 2.3	N/A	3.2 ± 5.6	75 %
α-Pinene	29.3	15.9 ± 1.4	N/A	9.3 ± 3.3	75 %
d-Limonene	4.3	1.8 ± 1.8	N/A	7.6 ± 5.0	25 %

[a] Lower numbers are better. Numbers after the ± represent geometric standard deviations.

Formaldehyde. Despite exceeding some formaldehyde health benchmarks, the NZERTF formaldehyde concentrations were lower than the other houses considered. This may be a function of the NZERTF not being furnished or occupied, both of which can contribute to elevated formaldehyde concentrations. The NZERTF geometric mean formaldehyde concentration was lower than all Indoor airPLUS homes and was in the lowest 10 % of measured formaldehyde concentrations in the CNHS. Homes in the Indoor airPLUS study were sampled during summer weather, which previous research has shown to lead to higher indoor concentrations of some VOCs (Poppendieck et al. 2015). The NZERTF formaldehyde geometric mean concentration during elevated summer months (May to September) was 11.8 μg/m^3, which is 36 % of the geometric mean value of the Indoor airPLUS homes.

Acetaldehyde. Despite exceeding acetaldehyde health benchmarks, the NZERTF acetaldehyde concentrations were lower or similar to the other houses considered. Only three of the 13 Indoor airPLUS homes had lower acetaldehyde concentrations than the geometric mean NZERTF concentration. The NZERTF acetaldehyde geometric mean concentration was below the geometric mean of the CNHS (Offermann 2009). The NZERTF acetaldehyde geometric mean concentration during summer months was 25.7 μg/m^3, which is 77 % of the average value of the 13 Indoor airPLUS criteria homes (sampled during summer months).

Other Chemicals. Eight other building material emission related chemicals are also listed in Table 4. For six of the eight remaining chemicals listed, the geometric mean concentration of the NZERTF samples was higher than that of the CNHS. This is in contrast to formaldehyde, where the NZERTF geometric mean concentration was lower than 98 % of the homes in the California study. Hence, for formaldehyde concentrations, the NZERTF outperforms these other homes built within a decade of its construction. This finding is likely due to the explicit construction specifications that limited formaldehyde in the building materials used and the fact that the NZERTF was not occupied or furnished. For most of the remaining chemicals in Table 4, there were no building specifications targeting these chemicals, due in part to lack of available content and emission data for these chemicals. In addition, the NZERTF has a lower air change rate than the average of the other data sets. Hence, one would expect if the emission rates are the same, the concentrations should be higher in the NZERTF. Even if the NZERTF does not perform better than comparable buildings with regards to these eight chemicals, for the three chemicals with health benchmarks listed in Table 3 (styrene, toluene, ethylene glycol), the geometric mean NZERTF concentrations are at least an order of magnitude below the health-based CRELs.

If a home designer or occupant finds that either desired health benchmarks or comparison benchmarks have not been met, reducing pollutant sources and/or increased ventilation can reduce indoor chemical concentrations. However, increased ventilation comes at a cost of increased energy use and the possibility of exceeding energy benchmarks.

Summary and Conclusions

Between July 2013 and June 2014, the Net-Zero Energy Residential Test Facility (NZERTF) in Gaithersburg, MD achieved net-zero energy consumption through the use of an on-site photovoltaic system, enhanced building envelope design, and efficient heating and cooling systems, appliances, and lighting. The home exceeded its goal and produced 484 kWh (1.65 MMBtu) of electrical energy that was returned to the grid. This study seeks to put the performance of the NZERTF into context by benchmarking for energy and indoor air quality. To summarize:

- The annual site energy use of the NZERTF was 13,039 kWh (44.5 MMBtu), 49.6 % of the national average (Table 1).
- The annual energy use intensity of the NZERTF was 33.8 kWh/m^2 (10.7 kBtu/ft^2), 23.5 % of the national average (Table 1).
- The NZERTF has a HERS index of -6 with photovoltaic energy generation and 31 without. This number compares well with the average HERS rated net-zero home (HERS = -7) and exceeds the average Maryland home (HERS = 57) (Table 2).
- The NZERTF has a Home Energy Yardstick score of 10 and a HUD Energy Benchmark score of 97.
- NZERTF concentrations of formaldehyde are in the lowest 10th percentile compared to recent surveys of new, occupied homes. However, these concentrations sometimes exceeded health benchmarks (Table 3).
- NZERTF concentrations of other volatile organic compounds (VOCs) on average tend to be higher than other homes surveyed (Table 4) and, with the exception of acetaldehyde, are below recommended exposure levels (Table 3).

High-performance-building designers desire a quantitative assessment of how energy upgrades and efforts to improve indoor air quality perform, but also need to be able to evaluate tradeoffs between the two goals. The authors contend that, while increasing energy efficiency and maintaining IAQ are linked, it is important to have standalone benchmarking evaluations of each, and a truly high-performance building would have high benchmarks for both. It has been established that energy benchmarking is a necessary tool for validating the design of homes like the NZERTF. The limitations in the past have been access to representative datasets and energy simulations, but that concern is no longer the case. The challenge for the indoor environment, however, is that there is no existing single benchmark metric for IAQ that allows comparisons among homes and such a benchmark may not be possible. In addition, datasets to support any benchmarks are lacking. Ideally there would be data available that summarizes the distribution of concentrations of hundreds of chemicals of concern in over a large number of residences both before and after occupation and in multiple climate regions. In addition, there would be known health impacts for both acute and lifetime exposures to all measured pollutants. More data are still needed to allow a proper discussion of what is “acceptable IAQ” in terms of measured pollutant concentrations.

Finally, this study illustrates a case of energy and IAQ benchmarking. There are other benchmarking metrics that have not been addressed which are still important in describing high-performance buildings. Thorough benchmarking should also consider thermal comfort, water usage, water quality, waste production, lighting quality, and acoustic performance, to name a few. Determination of representative datasets for benchmarking these aspects of a high-performance home may prove to be just as challenging as it is for IAQ.

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